Multiphase Parallel Interleaved And Primary-Parallel Secondary-Series Forward Micro-Inverter Comparison

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I. INTRODUCTION

Series connection of photovoltaic (PV) modules to supply a voltage-fed grid-connected inverter is the conventional solution to overcome the low voltage generated by PV arrays. However, the energy yield of these configurations is affected by mismatches between PV modules and partial-shading, especially in residential applications. Distributed MPPT (DMPPT) architectures improve the energy harvesting capability by means of a module integrated converter (MIC) [1,2]. AC-module application is a specific case of DMPPT in which a grid connected micro-inverter is attached to the back part of a PV-module.

The use of a transformer is common in AC-module application to achieve the necessary high voltage boost required to interface the low output voltage provided by the PV module to the grid. In buck-derived topologies, such as the forward micro-inverter presented in [3], a large turns ratio is needed, thus resulting in high leakage inductance and extra losses in the windings [4]. For this reason, in [4] a configuration with parallel-input and series-output connection of unitary turns ratio transformers is presented. This transformer configuration, which has been explored in different topologies [5-8], allows duplicating the primary side thus resulting in reduced current stress in the primary side and improved voltage gain. In the case of AC-module application the parallel-series configuration with synchronized primary switches and common-cathode secondary diodes has been applied to the forward micro-inverter presented in [9] to improve the overall inverter performance.

The use of parallel interleaved converters is common in low-voltage high-current applications. Besides the current stress in the components is decreased, the size of the magnetic components can be reduced and the efficiency at light load can be improved by dynamically connecting or disconnecting phases [10-12]. This phase shedding characteristic is interesting in photovoltaic applications, since the operation power range is wide due to the changeable irradiance and temperature conditions.

In both configurations, either the parallel interleaved or parallel-series connected, besides the increase in the number of components, increasing the number of converters implies challenges such as the current sharing and control complexity. However, the current stress is highly reduced allowing the use of surface mounted devices (SMD), even for the reactive components [13]. Furthermore, the losses are split in more components and the thermal management improved, making the use of heatsinks dispensable. As a result, a low profile implementation is possible and the micro-inverter can be mounted in the frame of the solar module [14].

This paper compares, in terms of size and losses, a classical multiphase interleaved with separate inductors and the parallel-series connected [9] configurations for a forward micro-inverter, analyzing the effect of varying the number of phases. Section II presents the two multiphase solutions to be analyzed. Section III and IV analyze the transformer size and performance and the calculated efficiency, respectively. Section V shows the experimental results for 8-transformers configurations to demonstrate the introduced analysis.

II. PARALLEL INTERLEAVED AND PARALLEL-SERIES FORWARD MICRO-INVERTER

The interleaving techniques for DC-DC buck-derived converters, such as the forward converters is well-known [15], and used in different applications for its advantages in light-load efficiency improvement, low-profile and easy thermal management. These characteristics make suitable the application of multiphase techniques to PV AC-module micro-inverters. In this paper the multiphase approach is applied to a forward micro-inverter with separate inductors, as depicted in Fig. 1.

The necessary large turns ratio in the forward transformer to overcome the required voltage boosting limits the performance of the micro-inverter. In [9] a multiphase forward micro-inverter with primary-parallel secondary-series connected transformers (Fig. 2) is presented to improve the conversion efficiency by enhancing the transformer coupling. In the presented topology, the primary switches are synchronized, being the number of active switches decided according to the grid voltage. The parallel-series connection allows achieving the grid voltage using lower turns ratio transformers as well as reducing the current stress in the semiconductors.

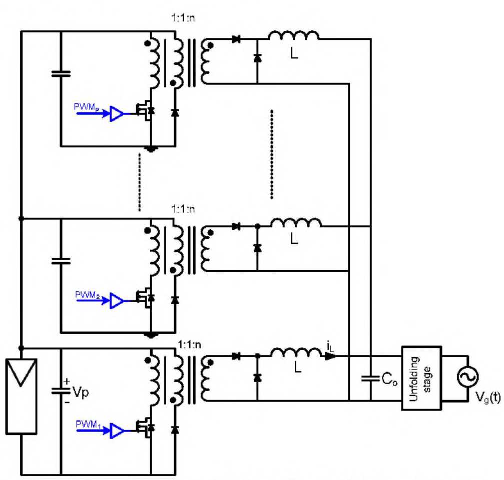


Fig. 1. Interleaved multiphase forward micro-inverter

In the presented comparison both configurations generate a rectified current which is unfolded in a line-frequency switched bridge. Both inverters are operated in discontinuous conduction mode (DCM) by applying the control law presented in (1), which theoretically guarantees unitary power factor current without current loop. In the presented control law 'n' is the transformer turns ratio, which remains constant in the interleaved configuration for a half-line period. However, its value changes in the parallel-series solution according to the number of active switches.

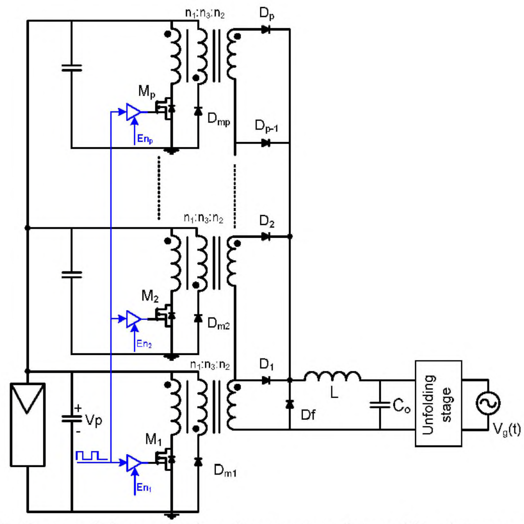


Fig. 2. Proposed forward micro-inverter topology with primary-parallel secondary-series connected transformers.

The critical inductance for both multiphase configurations to guarantee DCM operation can be calculated at grid peak voltage conditions 'V_{g_pk}' according to (2), being 'p' the total number of phases. In the parallel-series inverter p=1 since the output filter is equivalent to a 1-phase inverter.

$$d(t)=M(t)\cdot\sqrt{\frac{k_{DCM}}{n\cdot(n-M(t))}};\ k_{DCM}=\frac{2\cdot L\cdot f_{sw}}{V_{o\_RMS}^{2}}\cdot P_o;\ M(t)=\frac{v_o(t)}{Vp} \quad (1)$$

$$L_{crit\_DC}(p)=\frac{(n\cdot V_p-V_{g\_pk})\cdot V_{g\_pk}^{2}}{4\cdot n\cdot V_p\cdot P_o\cdot f_{sw}}\cdot p \quad (2)$$

III. SIZE COMPARISON AND TRANSFORMER PERFORMANCE

Size, cost and efficiency are main concerns in AC-module application [2]. The number of utilized phases in the interleaved topology, as well as in the parallel-series configuration, is closely related to these requirements due to several parameters such as input and output filter size, increase in the number of components and complexity of driving as well as elimination of heatsink.

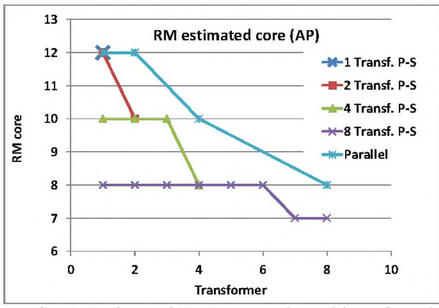
This section presents the impact in height and area of increasing the number of phases in the interleaved forward micro-inverter or the number of transformers in the parallel-series configuration. Since the transformer turns ratio is different for the two analyzed multiphase configurations, detailed designs of the selected transformers have been developed to analyze the influence of the number of phases in the leakage inductance, series resistance and losses of the selected transformers. In addition, an analysis of the effect of implementing a multiphase system on the decoupling capacitor and the output filter in introduced.

A. *Transformers Volume, Area and Height*

The transformer design is identified as a main contributor to the size as well as to the converter performance. The area product parameter (6) [16] is used to select the cores for configurations with 1, 2, 4 and 8 transformers for the parallel interleaved as well as the parallel-series inverters.

$$Ap = Ae \cdot Aw = \frac{Vp \cdot d_{\max}}{n_1 \cdot B_{\max} \cdot f_{\min}} \cdot \frac{1.2 \cdot (n_1 \cdot I_{RMS1} + n_2 \cdot I_{RMS2})}{k_w \cdot J_{\max}} \tag{6}$$

The parameters used to select the RM cores are shown in Fig. 3, together with the estimated cores for the different analyzed configurations of a 120W forward micro-inverter, with an input voltage of 45V and to be connected to the US grid.



Core type /material	RM/3C90
kw	0.3
Jmax	600 A/cm^2
Bmax	0.65·Bsat
V_{PV}	45V
P_{PV}	120W
Vgrid	110V

Fig. 3. Estimated RM cores selected based on the area product and parameters used for the selection.

Based on the selected cores using the area product parameter (Fig. 3), the total surface as well as the maximum height of the transformer set considering the bobbin has been estimated for each configuration. The total transformer volume is therefore calculated by the product of the estimated area and height. Fig. 9 shows the obtained results versus the number of phases, or transformers, for the interleaved (PP) and parallel-series (PS) configurations

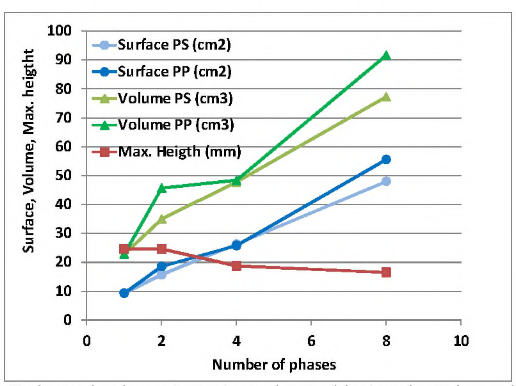


Fig. 4. Estimated volume (green), total area (blue) and maximum height (red) of the selected transformers.

In the case of the interleaved inverter the power is divided equitably among the phases. Therefore, all the phases have the same core, which matches with the biggest one of the parallel-series configuration for a given number of phases. As a consequence, the total surface and volume of the set of transformers is larger for the parallel interleaved inverter for a given number of transformers.

As shown in Fig. 4, the total estimated area increase with the number of phases as well as the total volume of the transformers. However, the maximum estimated height of the transformers decreases as the number of phases increase, being that the same for both multiphase configurations.

B. *Transformer Performance Comparison*

A loss optimized design of each transformer for the interleaved and parallel-series configurations is developed according to the selected RM cores presented in Fig. 8, in order to compare them in terms of losses, series resistance and leakage inductance. As shown in Fig. 5 the total losses as well as the losses per individual transformer are higher for the interleaved configuration. The core losses are calculated as an average of the core losses during a half-line cycle, while the conduction losses are calculated using finite element analysis in an equivalent DC-DC forward converter.

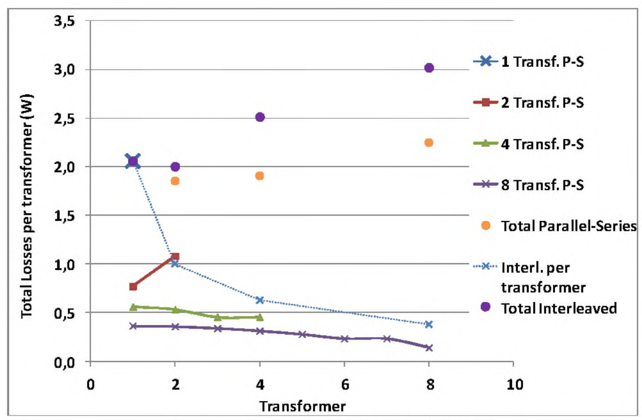
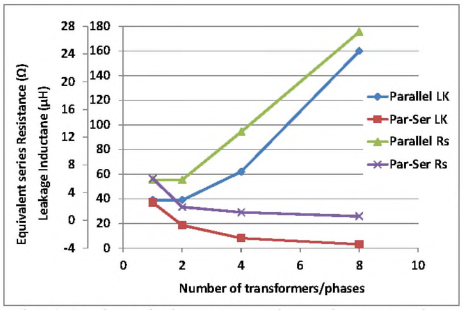


Fig. 5. Calculated transformer losses.

Leakage inductance and series resistance are closely related to switching and winding losses, i.e. the inverter performance. In the interleaved multiphase, the transformer turns ratio is the same independently of the number of phases and the core size is reduced. Consequently, increasing the number of phases leads to higher values of both parameters (Fig. 6). However, in the parallel-series connected inverter the individual transformer turns ratio gets closer to unity with the number of transformers, as shown in Fig. 6. Therefore, primary to secondary coupling is improved and leakage inductance and series resistance are sharply reduced (Fig. 6).



	Turns ratio	
Phases	Parallel	Parallel-Series
1	8	8
2	8	4
4	8	2
8	8	1

Fig. 6. Leakage inductance, series resistance and transformers turns ratio.

C. Output Filter and Input Capacitor

The necessary inductor for the two analyzed approaches, depicted in Fig. 1 and Fig. 2, using one transformer is the same and can be considered as a reference for output inductor size comparison. In the presented parallel-series topology the output filter remains the same independently of the number of utilized transformers, as depicted in Fig. 2.

However, increasing the number of parallel phases in the interleaved topology means higher number of output inductors, thus increasing the inverter area. On the other hand the inductor height is reduced at the same time than the transformer set maximum height. In addition, the output capacitor is reduced due to the reduced output current ripple due to interleaved operation (Fig. 7). It must be noticed that in AC-module application the converter is attached to the back side of a PV module and, therefore, the available area is large. Furthermore, the low height allows mounting the micro-inverter in the frame of the solar module [14].

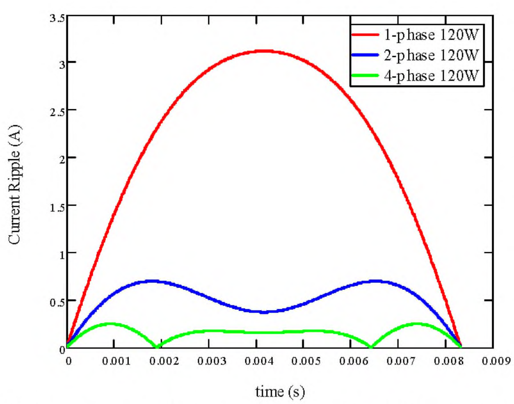


Fig. 7: Output current ripple at nominal load for different number of interleaved phases.

In the same manner, the decoupling input capacitor [17] can be split among the phases in both interleaved and parallel-series inverters, thus low-profile ceramic capacitors can be used.

IV. Efficiency Comparison

In PV applications efficiency is an important design target in order to maximize the energy harvested from the solar modules. Furthermore, due to the variations in temperature and irradiance conditions the available power range is wide and the efficiency needs to be assessed for different power levels according to [18]. In this operation frame the utilization of multiphase interleaved converters can provide performance improvement in the light-load operation by means of techniques such as phase shedding.

This section presents the influence of increasing the number of phases in the interleaved forward micro-inverter efficiency and a comparison with the parallel-series forward micro-inverter proposed in [9]. In the efficiency calculations magnetic components and semiconductor losses are considered for the power levels defined in the CEC efficiency definition [18]. Regarding the magnetic components, the inductor losses are obtained using a finite element simulation model in an equivalent buck converter, and the transformers losses are those introduced in the previous section. Considering the semiconductors, switches and reset diodes in the primary side, and secondary side diodes losses are calculated with the average values in a half line period, according to (5) and (6):

$$P_{Switch\_i} = 1.6 \cdot R_{DSon} \cdot \Big(\sum_{k,T_{grid}} I_{Mi\_RMS\_k}\Big)^2 + \frac{1}{2} \cdot \Big(\sum_{k,T_{grid}} V_{OFF\_i} \cdot I_{Mi\_pk}\Big) \cdot t_{fall} \cdot 2 \cdot f_{grid} \tag{5}$$

$$P_{Diode\_j} = V_{F\_j} \cdot \sum_{k,T_{grid}} I_{Dj\_avg\_k} \tag{6}$$

As shown in Fig. 8. Calculated efficiency for the analyzed configurations of the interleaved forward micro-inverter.Fig. 8, by increasing the number of paralleled phases the performance of the micro-inverter is improved, especially at light load. According to this efficiency behavior the CEC efficiency can be improved by increasing the number of phases (Fig. 9) despite the high-load performance is slightly jeopardized.

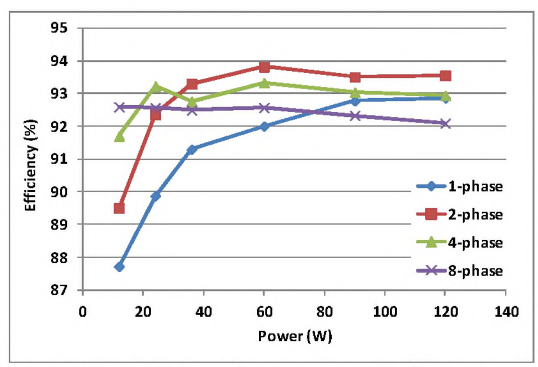


Fig. 8. Calculated efficiency for the analyzed configurations of the interleaved forward micro-inverter.

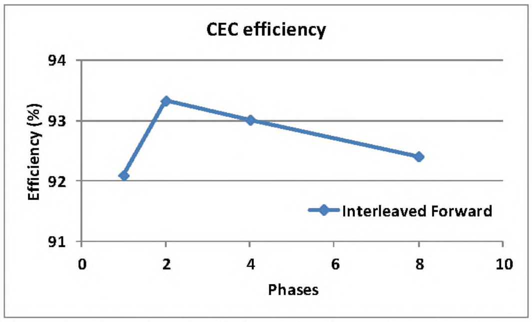


Fig. 9. Calculated CEC efficiency for the analyzed interleaved configurations

The introduced efficiency for the interleaved micro-inverter has been compared with the obtained efficiency for the primary-parallel secondary-series micro-inverter presented in [9]. Fig. 10 shows the efficiency comparison for the 8-phase configurations and the single transformer one. As expected the phase shedding capability of the interleaved solution improves the light-load performance. The expected efficiency for the parallel-series solution is similar to the single-transformer micro-inverter, except for the light-load range where the high number of active switches jeopardizes the efficiency, slightly decreasing the weighted efficiency. However, it must be noticed that the single-transformer and the interleaved designs present large primary to secondary turns ratio, i.e. the transformer leakage inductance and series resistance are high. The effect of those parameters is not included in the calculations and therefore, the expected efficiency in these configurations is expected to be lower.

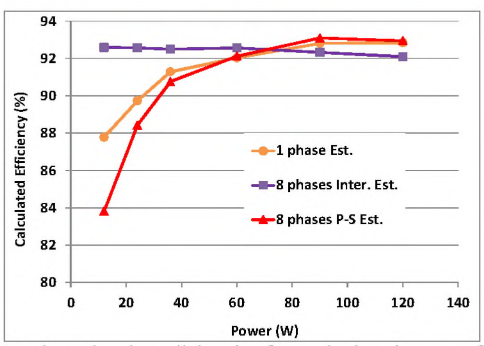


Fig. 10: Interleaved and parallel-series forward micro-inverter efficiency comparison.

V. EXPERIMENTAL RESULTS

Two multiphase prototypes of 120W with eight transformers of the parallel-series (Fig. 16.c) and the interleaved (Fig. 16.b) micro-inverters have been built to interface a 45V, 120W PV module to the 110V@60Hz grid. Also a single transformer forward micro-inverter is built (Fig. 16.a) to compare the results to the multiphase configurations. The transformer turns ratio of the different prototypes are presented in Fig. 6. The area of the multiphase prototypes is 25x20cm for the parallel-series micro-inverter, and 30x20cm for the interleaved one. The maximum height of the parallel-series prototype is limited by the output inductor (3cm), which is the same for the single-transformer prototype. In the case of the parallel interleaved prototype the height is fixed by the transformers in 1.65cm, as calculated in section III.A. The presented results are obtained for a fixed input voltage of 45V and the grid connection is emulated with an AC voltage source in parallel with a resistor. The same primary switch (IRFS4410PbF) and same secondary side SiC diode (C3D02060E) is used for all the prototypes. The control of the presented prototypes is implemented in a TMS320F28069 microcontroller.

The output voltage, injected current and inductor current of phases 2 and 4 waveforms of the interleaved micro-inverter at full load are presented in Fig. 12. The same waveforms for half load operation are depicted in Fig. 13. It can be observed how the phase angle between phases changes with the number of active phases, thus keeping the interleaving behavior. In all the cases the output inductance is designed to be in boundary conduction mode at the peak voltage and nominal power, as it can be seen in the high-frequency operation waveforms of Fig. 13. The main waveforms of the parallel-series micro-inverter at nominal power are presented in Fig. 14.

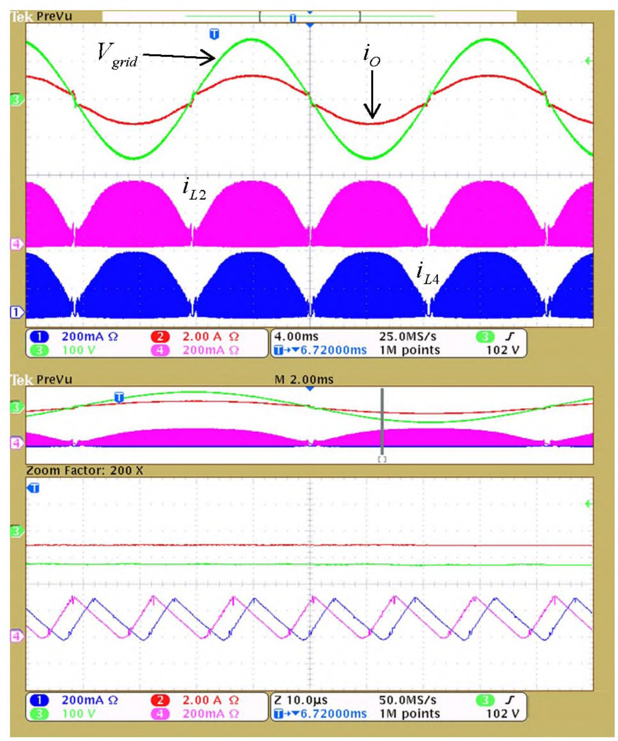


Fig. 12. AC and high-frequency 120W (8 phases) interleaved forward micro-inverter waveforms

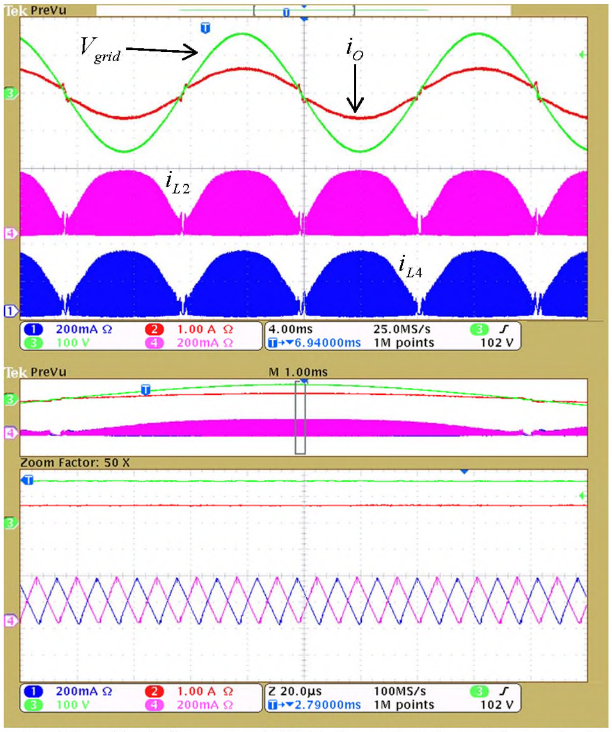


Fig. 13. AC and high-frequency 60W (4 phases) interleaved forward micro-inverter waveforms

Fig. 14. 8-phase parallel-series prototype AC and high frequency waveforms at full-load

Fig. 15 shows the measured efficiency for the three prototypes at the different power levels defined by the CEC weighted efficiency. The light-load and the full-load efficiency are slightly improved in the interleaved configuration, contributing to improve the CEC efficiency from 90.13% for the single-transformer micro-inverter to 90.88% for the 8-phase interleaved prototype. According to Fig. 15 the parallel-series prototype presents a better performance for the most of the power range, thus improving the weighted efficiency to 92.37%.The measured THD of the interleaved solution is slightly above7% for all the tested powers with a power factor (PF) over 0.994.

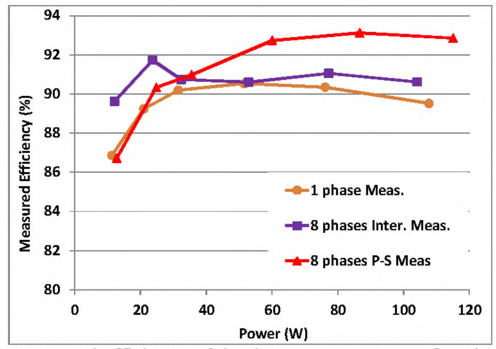
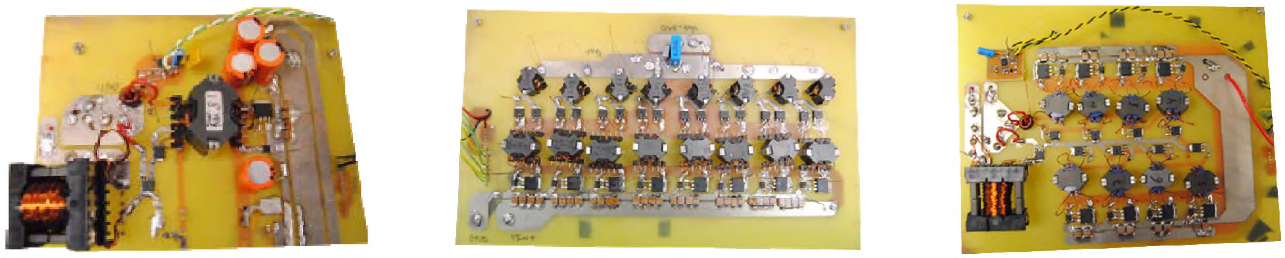


Fig. 15. Measured efficiency of the three prototypes as a function of the injected power.

VI. CONCLUSIONS

This paper presents the comparison between parallel and parallel-series multiphase implementation in a forward micro-inverter. In both cases increase the number of phases allows a height reduction, making the solution suitable for AC-module applications. The parallel interleaved implementation leads to higher area (20%) but lower height (45%) than the parallel-series connected one, which maximum height is limited by the output inductor. However, the parallel-series connection of transformers contributes to a better coupling, thus reducing leakage inductance and series resistance and improving the inverter weighted efficiency in about 2%.



a) b) c)

Fig. 16. Single transformer (a), 8 phases interleaved (b) and 8-transformer parallel-series (c) prototypes